Claims

What is claimed is:

1. A method for correcting skin effect in a induction logging system, said method comprising the steps of:

measuring first, second and third apparent conductivities at first, second and third operating frequencies, respectively;

determining first, second and third weighting coefficients;

determining first, second and third weights;

determining a first low-pass filtered conductivity difference between the measured first and second apparent conductivities;

determining a second low-pass filtered conductivity difference between the measured second and third apparent conductivities;

determining a third low-pass filtered conductivity difference between the measured first and third apparent conductivities;

determining a first corrected conductivity from the measured first, second and third apparent conductivities, the first, second and third weighting coefficients, and the first weight;

determining a second corrected conductivity from the first corrected conductivity, the second weight, the third low-pass filtered conductivity difference, and the first and third operating frequencies;

determining a third corrected conductivity from the second corrected conductivity, the first low-pass filtered conductivity difference, the second low-pass filtered conductivity difference, the first, second and third operating frequencies, and the third weight;

determining first, second and third compensated conductivities from the first, second and third corrected conductivities, respectively, and values from a look-up table;

determining selection coefficients; and

determining a formation corrected conductivity by summing the selection coefficients combined with the first, second and third compensated conductivities.

2. The method according to claim 1, wherein the sum of the selection coefficients equals one.

3. The method according to claim 1, wherein the step of determining the first low-pass filtered conductivity difference comprises the steps of subtracting the second apparent conductivity from the first apparent conductivity and low-pass filtering the difference.

4. The method according to claim 1, wherein the step of determining the second low-pass filtered conductivity difference comprises the steps of subtracting the third apparent conductivity from the second apparent conductivity and low-pass filtering the difference.

5. The method according to claim 1, wherein the step of determining the third low-pass filtered conductivity difference comprises the steps of subtracting the third apparent conductivity from the first apparent conductivity and low-pass filtering the difference.

6. The method according to claim 1, wherein the step of low-pass filtering controls random noise.

7. The method according to claim 1, wherein the step of low-pass filtering substantially matches response functions of the first and second conductivity differences to geometrical factors of the skin effect, wherein the first and second conductivity differences are substantially the apparent conductivity differences with respect to the square root of the operating frequencies.

8. The method according to claim 1, wherein the first weight is determined by:

$$w_1 = \frac{1}{\lambda_1 + \lambda_2 + \lambda_3}$$

where w1 is the first weight; and $\lambda 1$, $\lambda 2$ and $\lambda 3$ are the first, second and third weighting coefficients, respectively.

9. The method according to claim 1, wherein the second weight is determined by:

$$w_2 = \frac{\lambda_1\sqrt{f_1} + \lambda_2\sqrt{f_2} + \lambda_2\sqrt{f_3}}{\lambda_1 + \lambda_2 + \lambda_3}$$

where w_2 is the second weight; λ_1, λ_2 and λ_3 are the first, second and third weighting coefficients, respectively; and f_1, f_2 and f_3 are the first, second and third operating frequencies, respectively.

10. The method according to claim 1, wherein the third weight is determined by:

$$w_3 = \frac{\sqrt{f_1}(\sqrt{f_1} + \sqrt{f_3})(\lambda_1\sqrt{f_3} + \lambda_2\sqrt{f_2} + \lambda_3\sqrt{f_3}) - \lambda_2\sqrt{f_2}(f_2 - f_3)}{(\lambda_1 + \lambda_2 + \lambda_3)(\sqrt{f_1} + \sqrt{f_2} + \sqrt{f_3})(\sqrt{f_1} - \sqrt{f_3})}$$

where w_3 is the third weight; λ_1, λ_2 and λ_3 are the first, second and third weighting coefficients, respectively; and f_1, f_2 and f_3 are the first, second and third operating frequencies, respectively.

11. The method according to claim 1, wherein the first corrected conductivity is determined by:

$$\sigma_{sec0} = w_1(\lambda_1\sigma_{a1} + \lambda_2\sigma_{a2} + \lambda_3\sigma_{a3})$$

where σ_{sec0} is the first corrected conductivity; w_1 is the first weight; σ_{a1}, σ_{a2} and σ_{a3} are the measured first, second and third apparent conductivities, respectively; and λ_1, λ_2 and λ_3 are the first, second and third weighting coefficients, respectively.

12. The method according to claim 1, wherein the second corrected conductivity is determined by:

$$\sigma_{sec1} = \sigma_{sec0} + w_2\left(\frac{\sigma_{a1} - \sigma_{a3}}{\sqrt{f_1} - \sqrt{f_3}}\right) * h$$

where σ_{sec1} is the second corrected conductivity; σ_{sec0} is the first corrected conductivity; w_2 is the second weight; σ_{a1} and σ_{a3} are the measured first and third apparent conductivities, respectively; f_1 and f_3 are the first and third operating frequencies, respectively; and h is the low-pass filtering.

13. The method according to claim 1, wherein the third corrected conductivity is determined by:

$$\sigma_{sec2} = \sigma_{sec1} + w_3\left(\frac{\sigma_{a1} - \sigma_{a2}}{\sqrt{f_1} - \sqrt{f_2}} - \frac{\sigma_{a2} - \sigma_{a3}}{\sqrt{f_2} - \sqrt{f_3}}\right) * h$$

where σ_{sec2} is the third corrected conductivity; σ_{sec1} is the second corrected conductivity; w_3 is the third weight; σ_{a1}, σ_{a2} and σ_{a3} are the measured first, second and third apparent conductivities, respectively; f_1, f_2 and f_3 are the first, second and third operating frequencies, respectively; and h is the low-pass filtering.

14. The method according to claim 1, wherein the formation corrected conductivity is determined by: $\sigma_{sec} = \alpha\sigma_{s0} + \beta\sigma_{s1} + \gamma\sigma_{s2}$, where σ_{sec} is the formation corrected conductivity; α, β and γ are the selection coefficients; and σ_{s0}, σ_{s1} and σ_{s2} are the first, second and third compensated conductivities, respectively.

15. The method according to claim 1, wherein the values of the look-up table are determined comprising the steps of:

a) setting $i = 1$

b) selecting a discrete formation conductivity value (σ_t^i);

c) computing the first, second and third apparent conductivities (σ_{a1}, σ_{a2} and σ_{a3});

d) determining first, second and third weighting coefficients (λ_1, λ_2 and λ_3);

e) determining first, second and third weights (w_1, w_2 and w_3);

f) determining a first conductivity difference (σ_{12}) between the measured first and second apparent conductivities (σ_{a1} - σ_{a2});

g) determining a second conductivity difference (σ_{23}) between the measured second and third apparent conductivities (σ_{a2} - σ_{a3});

h) determining a third conductivity difference (σ_{13}) between the measured first and third apparent conductivities (σ_{a1} - σ_{a3});

i) determining a first corrected conductivity (σ_{sec0}^i) from the measured first, second and third apparent conductivities (σ_{a1}, σ_{a2} and σ_{a3}), the first, second and third weighting coefficients (λ_1, λ_2 and λ_3) and the first weight (w_1);

j) determining a second corrected conductivity (σ_{sec1}^{i}) from the first corrected conductivity (σ_{sec0}^{i}), the second weight (w_2), the third conductivity difference (σ_{13}), and the first and third operating frequencies (f_1 and f_3);

k) determining a third corrected conductivity (σ_{sec2}^{i}) from the second corrected conductivity (σ_{sec1}^{i}), the first conductivity difference (σ_{12}), the second conductivity difference (σ_{23}), the first, second and third operating frequencies (f_1, f_2 and f_3), and the third weight (w_3);

l) setting compensated conductivites (σ_{s0}^{i}, σ_{s1}^{i}, σ_{s2}^{i}) equal to a formation conductivity value;

m) storing the first, second and third corrected conductivities (σ_{sec0}^{i}, σ_{sec1}^{i}, σ_{sec2}^{i}), the compensated conductivites (σ_{s0}^{i}, σ_{s1}^{i}, σ_{s2}^{i}) and the selected discrete formation conductivity value (σ_t^i) in an i^{th} row of the look-up table values; and

n) incrementing $i = i + 1$ and repeating steps b) through n) until i = N, whereby the look-up table values are defined by the discrete formation conductivity values (σ_t^i) , where i is a positive integer value from 1 to N.

16. The method according to claim 1, wherein the step of determining selection coefficients comprises the steps of determining the selection coefficients by turning points (C_A and C_B) and transition widths (T_A and T_B) of a formation conductivity graph.

17. The method according to claim 1, wherein the first, second and third operating frequencies may be selected from about 5 kilohertz to about 500 kilohertz.

18. A method for correcting skin effect in a induction logging system, said method comprising the steps of:

measuring first and second apparent conductivities at first and second operating frequencies, respectively;

determining first and second weighting coefficients;

determining first and second weights;

determining a low-pass filtered conductivity difference between the measured first and second apparent conductivities;

determining a first corrected conductivity from the measured first and second apparent conductivities, the first and second weighting coefficients, and the first weight;

determining a second corrected conductivity from the first corrected conductivity, the second weight, the low-pass filtered conductivity difference, and the first and second operating frequencies;

determining first and second compensated conductivities from the first and second corrected conductivities, respectively, and a look-up table;

determining selection coefficients; and

determining a formation corrected conductivity by summing the selection coefficients combined with the first and second compensated conductivities.

19. The method according to claim 18, wherein the sum of the selection coefficients equals one.

20. The method according to claim 18, wherein the step of determining the first low-pass filtered conductivity difference comprises the steps of subtracting the second apparent conductivity from the first apparent conductivity and low-pass filtering the difference.

21. The method according to claim 18, wherein the step of low-pass filtering controls random noise.

22. The method according to claim 18, wherein the step of low-pass filtering substantially matches geometric factors of formation skin effect in relation to the square root of the operating frequencies.

23. The method according to claim 18, wherein the first weight is determined by:

$$w_1 = \frac{1}{\lambda_1 + \lambda_2}$$

where w_1 is the first weight; and λ_1 and λ_2 are the first and second weighting coefficients, respectively.

24. The method according to claim 18, wherein the second weight is determined by:

$$w_2 = \frac{\lambda_1\sqrt{f_1} + \lambda_2\sqrt{f_2}}{\lambda_1 + \lambda_2}$$

where w_2 is the second weight; λ_1 and λ_2 are the first and second weighting coefficients, respectively; and f_1 and f_2 are the first and second operating frequencies, respectively.

25. The method according to claim 18, wherein the first corrected conductivity is determined by: $\sigma_{sec0} = w_1(\lambda_1\sigma_{a1} + \lambda_2\sigma_{a2})$, where σ_{sec0} is the first corrected conductivity; w_1 is the first weight; σ_{a1} and σ_{a2} are the measured first and second apparent conductivities, respectively; and λ_1 and λ_2 are the first and second weighting coefficients, respectively.

26. The method according to claim 18, wherein the second corrected conductivity is determined by:

$$\sigma_{sec1} = \sigma_{sec0} + w_2\left(\frac{\sigma_{a1} - \sigma_{a2}}{\sqrt{f_1} - \sqrt{f_2}}\right) * h$$

where σ_{sec1} is the second corrected conductivity; σ_{sec0} is the first corrected conductivity; w_2 is the second weight; σ_{a1} and σ_{a2} are the measured first and second apparent conductivities, respectively; f_1 and f_2 are the first and second operating frequencies, respectively; and h is the low-pass filtering.

27. The method according to claim 18, wherein the formation corrected conductivity is determined by: $\sigma_{sec} = \alpha\sigma_{s0} + \beta\sigma_{s1}$, where σ_{sec} is the formation corrected conductivity; α and β are the selection coefficients; and σ_{s0} and σ_{s1} are the first and second compensated conductivities, respectively.

28. The method according to claim 18, wherein the first and second operating frequencies may be selected from about 5 kilohertz to about 500 kilohertz.

29. A method for correcting skin effect in a induction logging system, said method comprising the steps of:

measuring two or more apparent conductivities at two or more operating frequencies;

determining weighting coefficients;

determining weights;

determining a low-pass filtered conductivity difference between the two or more apparent conductivities;

determining a first corrected conductivity from the measured two or more apparent conductivities, the weighting coefficients, and the weights;

determining a second corrected conductivity from the first corrected conductivity, the weights, the low-pass filtered conductivity difference, and the two or more operating frequencies;

determining first and second compensated conductivities from the first and second corrected conductivities, respectively, and a look-up table;

determining selection coefficients;

combining the selection coefficients with the first and second compensated conductivities; and

summing the combined selection coefficients and the first and second compensated conductivities to obtain a formation corrected conductivity.

30. The method according to claim 29, wherein the sum of the selection coefficients equals one.

31. The method according to claim 29, wherein the step of determining the low-pass filtered conductivity difference comprises the steps of subtracting one of the two or more apparent conductivities from the other two or more apparent conductivities and low-pass filtering the difference.

32. The method according to claim 29, wherein the step of low-pass filtering controls random noise.

33. The method according to claim 29, wherein the step of low-pass filtering substantially matches geometric factors of formation skin effect in relation to the square root of the operating frequencies.

34. The method according to claim 29, wherein the operating frequencies may be selected from about 5 kilohertz to about 500 kilohertz.

35. A method for correcting skin effect in a induction logging system, said method comprising the steps of:

measuring at least two apparent conductivities at two or more operating frequencies;

determining weighting coefficients;

determining weights;

determining a low-pass filtered conductivity difference between the at least two apparent conductivities;

determining at least two corrected conductivities from the measured at least two apparent conductivities, the weighting coefficients, the weights, the low-pass filtered conductivity difference and the two or more operating frequencies;

determining at least two compensated conductivities from the at least two corrected conductivities and a look-up table;

determining selection coefficients; and

determining a formation corrected conductivity from the at least two compensated conductivities and the selection coefficients.

36. The method according to claim 35, wherein the operating frequencies may be selected from about 5 kilohertz to about 500 kilohertz.

37. An induction logging system having skin effect correction, said system comprising:

an induction logging tool for measuring first, second and third apparent conductivities at first, second and third operating frequencies, respectively;

a processor, wherein:

the processor receives the measured first, second and third apparent conductivities from the induction logging tool;

the processor determines first, second and third weighting coefficients;

the processor determines first, second and third weights;

the processor determines a first low-pass filtered conductivity difference between the measured first and second apparent conductivities;

the processor determines a second low-pass filtered conductivity difference between the measured second and third apparent conductivities;

the processor determines a third low-pass filtered conductivity difference between the measured first and third apparent conductivities;

the processor determines a first corrected conductivity from the measured first, second and third apparent conductivities, the first, second and third weighting coefficients, and the first weight;

the processor determines a second corrected conductivity from the first corrected conductivity, the second weight, the third low-pass filtered conductivity difference, and the first and third operating frequencies;

the processor determines a third corrected conductivity from the second corrected conductivity, the first low-pass filtered conductivity difference, the second low-pass filtered conductivity difference, the first, second and third operating frequencies, and the third weight;

the processor determines first, second and third compensated conductivities from the first, second and third corrected conductivities, respectively, and values from a look-up table;

the processor determines selection coefficients; and

the processor determines a formation corrected conductivity by summing the selection coefficients combined with the first, second and third compensated conductivities.

38. The system according to claim 37, further comprising a display system for displaying the formation corrected conductivity.

39. The system according to claim 37, further comprising a control system for communicating with the logging tool and providing parameters thereto.

40. The system according to claim 39, wherein the parameters are the first, second and third operating frequencies.

41. The system according to claim 37, wherein the induction logging tool comprises at least one pair of transmitting and receiving electromagnetic induction coils separated by a distance.

42. The system according to claim 41, wherein the distance between the at least one pair of transmitting and receiving electromagnetic induction coils may be from about 5 inches to about 150 inches.

43. The system according to claim 41, wherein the at least one pair of transmitting and receiving electromagnetic induction coils comprises a plurality of transmitting and receiving electromagnetic induction coil pairs separated in various distances from about 5 inches to about 150 inches.

44. The system according to claim 37, wherein the processor is a computer controlled by a software program.

45. The system according to claim 37, wherein the processor is in the induction logging tool.

46. The system according to claim 39, wherein the processor is in the control system.

47. An induction logging system having skin effect correction, said system comprising:
an induction logging tool for measuring at least two apparent conductivities at two or more operating frequencies;
a processor, wherein:
the processor receives the measured at least two apparent conductivities from the induction logging tool;
the processor determines weighting coefficients;
the processor determines weights;
the processor determines a low-pass filtered conductivity difference between at least two apparent conductivities;
the processor determines at least two corrected conductivity from the measured at least two apparent conductivities, the weighting coefficients, the weights, the low-pass filtered conductivity difference and the two or more operating frequencies;
the processor determines at least two compensated conductivities from the at least two corrected conductivities and a look-up table;
the processor determines selection coefficients; and
the processor determines a formation corrected conductivity from the at least two compensated conductivities and the selection coefficients.

48. The system according to claim 47, wherein the induction logging tool comprises at least one pair of transmitting and receiving electromagnetic induction coils separated by a distance.

49. The system according to claim 48, wherein the distance between the at least one pair of transmitting and receiving electromagnetic induction coils may be from about 5 inches to about 150 inches.

50. The system according to claim 48, wherein the at least one pair of transmitting and receiving electromagnetic induction coils comprises a plurality of transmitting and receiving electromagnetic induction coil pairs separated in various distances from about 5 inches to about 150 inches.